

Infrared thermographic analysis of surface temperature of the hands during exposure to normobaric hypoxia

Warwick Altitude Research Group

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Title: Infra-red thermographic analysis of surface temperature of the hands during exposure to normobaric hypoxia

Authors: Daniel Jones¹, Samuel F. Covins¹, Gavin E. Miller¹, Kenneth I. Morrison¹, Alexander G. Clark¹, Samuel D. Calcott¹, Alasdair M. Anderson¹, Samuel J.E. Lucas² Christopher H.E. Imray^{1,3} and the Warwick Altitude Research Group

¹*Warwick Medical School, University of Warwick, UK.*

²*School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, UK*

³*University Hospital of Coventry & Warwickshire NHS Trust, UK*

Corresponding Author

Name: Samuel F. Covins
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Email: s.f.covins@warwick.ac.uk

Author Details

Name: Daniel Jones
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Name: Samuel F. Covins (*Corresponding Author*)
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Name: Gavin E. Miller
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Name: Kenneth I. Morrison
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Name: Alexander G. Clark
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Name: Samuel D. Calcott
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Name: Alasdair M. Anderson
Address: Medical Teaching Centre
Gibbet Hill Campus
University of Warwick
Coventry
CV4 7AL

Name: Samuel J.E. Lucas
Address: School of Sport, Exercise and Rehabilitation Sciences
University of Birmingham
Edgbaston
Birmingham
B15 2TT

Name: Christopher H.E. Imray
Address: Department of Vascular Surgery
University Hospitals Coventry and Warwickshire NHS Trust
Clifford Bridge Road
Coventry CV2 2DX
Warwick Medical School
Coventry CV4 7AL
UK

Name: Warwick Altitude Research Group

Address: Medical Teaching Centre

Gibbet Hill Campus

University of Warwick

Coventry

CV4 7AL

Abstract (200 words)

Frostbite and other cold-related injuries commonly develop during prolonged exposure to the low environmental temperatures of polar and mountainous regions. Hypoxia is a potent sympathetic stimulus that causes vasoconstriction of the peripheral blood vessels, which may further compound the risk of developing a cold-related injury during high altitude exposure. To investigate this, we utilised portable infra-red thermographic technology to quantitatively measure changes in the surface temperature of the hands during exposure to increasing levels of normobaric hypoxia in a temperature-controlled high-altitude simulation. Surface temperature was assessed at four anatomical locations on both the left and right hands in a cohort of 10 healthy male participants at a series of pre-determined levels of hypoxia (0.20 $F_{I}O_2$ (pre- and post-exposure), 0.172 $F_{I}O_2$, 0.145 $F_{I}O_2$, 0.128 $F_{I}O_2$). Thermographic analysis revealed an overall decrease in peripheral temperature across the anatomical regions of the hands as the hypoxic stimulus increased, with statistically significant reductions observed at all four anatomical sites during exposure to 0.128 $F_{I}O_2$ ($p < 0.05$). These findings demonstrate that portable infra-red thermography can be used to detect reductions in peripheral surface body temperature during exposure to normobaric hypoxia.

Keywords (5-6 words)

Thermal imaging, cold-related injuries, frostbite, hypoxia

Introduction

Frostbite and non-freezing cold injuries develop during prolonged exposure to low environmental temperatures. Frostbite is a condition characterised by freezing of the skin and underlying tissues, resulting in damage to the peripheral microvasculature [Imray et al. 2009]. Severe cases of frostbite that do not receive early and appropriate treatment can have devastating and often debilitating consequences, including amputation and chronic disability [Imray et al. 2009, Imray et al. 2011, Murphy et al. 2000]. Early diagnosis and treatment is therefore essential in ensuring a positive overall outcome. However, as these injuries are rare and tend to occur in remote and austere environments where access to medical assistance is limited, it is often difficult for affected individuals to seek and receive appropriate treatment [Sachs et al. 2015]. Several factors are known to contribute to the development of frostbite, including: absolute temperature; wind chill; duration of cold exposure, and the quality of protective clothing [Gross et al. 2012, Hallam et al. 2010, Ikaheimo et al. 2011, Valnicek et al. 1993], but the role of hypoxia in the development of cold-related injuries remains unclear.

The peripheral vascular responses to hypoxia are dependent upon the complex interplay between the vasoconstrictive and vasodilatory mechanisms that regulate blood flow to the extremities. The complexities of these regulatory mechanisms have been attributed to differences in both the anatomy and autonomic innervation of the peripheral tissues [Minson, C.T. 2003]. Previous studies investigating the impact of high altitude on the peripheral circulation have demonstrated that exposure to acute hypoxia leads to a profound vasoconstriction of the cutaneous microvasculature [Durand et al. 1969, Wood et al. 1970, Weil et al. 1971, Fahim, M. 1992], which has been shown to correlate with an increase in sympathetic nerve activity [Kollai M. 1983]. Interestingly, this peripheral vasoconstriction response has also been observed in populations of high altitude residents, although their vascular responses were shown to be markedly reduced in comparison to sea level residents [Passino et al. 1996]. Taken together, it is plausible that this hypoxia-mediated

vasoconstrictive response may further compound the risk of cold-related injuries during exposure to low environmental temperatures.

Infra-red thermography (IRT) is a non-contact, non-invasive imaging technique for the assessment of surface body temperature. IRT has a well-established role in the monitoring of skin temperature changes in a variety of settings. Several studies have utilised infra-red imaging techniques to investigate regional skin temperature changes during exercise [Zontak et al. 1998, Formenti et al. 2013 de Andrade Fernandes et al. 2016]. IRT has also been utilised in several occupational studies exploring the impact of different working conditions on the surface temperature of the hands [Gold et al. 2004, Tirloni et al. 2017]. In addition, a number of clinical studies have been conducted to evaluate the success of anaesthetic nerve blocks using IRT to detect increases in skin temperature [Stevens et al. 2006, Lange et al. 2011]. In recent years, the clinical utility of IRT has increased dramatically and thermal imaging cameras have already shown promise in the diagnosis and monitoring of several important health conditions, including diabetic neuropathy and peripheral vascular disease [Lahiri et al. 2012]. The FLIR One thermographic smart photo adaptor is a portable, relatively inexpensive digital tool, compatible with most smart phones, capable of capturing a thermal image with a resolution of 0.1°C. In this study, we sought to utilise this device to image and quantify the surface body temperature of the hands during exposure to increasing levels of normobaric hypoxia. We hypothesised that exposure to hypoxia would lead to a decrease in peripheral temperature, as previously described [Durand et al. 1969, Wood et al. 1970, Weil et al. 1971, Fahim, M. 1992], and that these reductions would be detectable using the FLIR One device.

Materials and Methods

Study Design

The study was conducted in a normobaric environmental chamber located at the School of Sport, Exercise & Rehabilitation Sciences, University of Birmingham, UK (located at 160 m above sea level, mean barometric pressure: 761 ± 6 mmHg). Participants were exposed to a graded profile of normobaric hypoxia over an 8-hour period. Four pre-determined levels of hypoxia ($F_{I}O_2$) were chosen for the purposes of experimentation: 0.20 (466 m; $P_{I}O_2$: 142.9 ± 1.2 mmHg) pre- and post-exposure, 0.172 (1,740 m; $P_{I}O_2$: 122.9 ± 1.1 mmHg), 0.145 (3,207 m; $P_{I}O_2$: 103.6 ± 0.9 mmHg) to 0.128 (4,167 m; $P_{I}O_2$: 91.4 ± 0.8 mmHg). Participants spent a total of 90 minutes at each level of hypoxia (with the exception of the 0.20 $F_{I}O_2$ post-exposure level which was shortened to 45 minutes due to logistical reasons), with experimentation taking place 30 minutes after exposure to allow sufficient time for their immediate physiological responses to stabilise. Experimentation was conducted over several days with groups of 3-4 participants completing the ascent together. Chamber temperature ($20.0^{\circ}C$) and humidity (40% relative humidity) remained constant throughout the duration of experimentation across all the study days.

Participants

A total of 10 male participants were recruited to take part in the study. Demographic and biometric characteristics were as follows: (mean \pm SD) age 24.6 ± 1.8 years, height 182.0 ± 5.6 cm, body mass 79.68 ± 8.3 kg. All were non-smokers with no significant medical history. No participant had been exposed to high altitude within 6 months prior to experimentation. All participants were requested to avoid alcohol consumption for 12 hours and caffeine consumption for 6 hours preceding experimentation.

Ethics

The study was approved by the Biomedical Science Research Ethics Committee (BSREC) at the University of Warwick, UK, and was conducted in accordance with the standards of

the Declaration of Helsinki. Experimental procedures were explained to all participants, and all gave informed written consent before taking part in the study.

Measurements

Routine clinical measurements, including core body temperature and blood oxygen saturation (SpO₂) were recorded at each of the pre-designated levels of hypoxia. Core temperature was measured using an MSR ST613 Tympanic Thermometer [ProAct Medical Ltd, Corby, UK]. Measurements of SpO₂ were performed using a C19 transcutaneous finger-tip pulse oximeter [Timesco Healthcare Ltd, Basildon, UK] attached to the index finger of the right hand.

Thermographic Imaging

Infra-red thermography was performed using a FLIR One thermal imaging camera attachment [FLIR Systems Ltd, West Malling, Kent, UK] for the Apple iPhone 6 [Apple Inc. Cupertino, California, USA].

For imaging purposes, participants were asked to place their hands over a 90 cm x 90 cm background of medium density fibreboard (MDF) with their fingers spread equally. The FLIR One camera was positioned 30 cm away MDF backboard. A single image of the dorsum of both hands was taken at each level of hypoxia. Participants were instructed to wear non-restrictive clothing for the duration of the study and were asked to keep their hands exposed at all times. During the 30 minutes of acclimatisation at each level, participants were further instructed not to touch any objects and avoid any hand-to-hand contact.

Calibration of Equipment

Calibration of the FLIR One camera was performed using the in-app settings, in accordance with the manufacturer's guidelines. The device was calibrated immediately prior to experimentation on each study day.

Data Analysis

Visual inspection of the data was conducted to identify any obvious artefacts or any distortion of the images. Measurements of peripheral temperature readings from the captured images was performed retrospectively using the FLIR One in-app software version 2.0 [FLIR Systems Ltd, West Malling, Kent, UK]. Temperature readings were recorded at four anatomically distinct regions: the 3rd digit of both the left and right hands; the nail bed, distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint, and metacarpophalangeal (MCP) joint hand [Figure 1]. Temperature measurement at each of these anatomical locations was achieved using a cursor that selects a user-defined area of the image and calculates an average reading across the selected pixels. In this study, the default area size (1 mm x 1 mm) was selected for temperature analysis, which incorporates the readings of approximately four individual pixels of image captured using the FLIR One device. For the purposes of data analysis, an average temperature reading was calculated across both hands at each of the selected anatomical regions.

Statistical Analysis

Changes in temperature (core and hand site) were compared via a two-way analysis of variance (ANOVA), and a one-way ANOVA was used to assess changes in oxygen saturations across the different levels of hypoxia. Interaction and main effects were isolated using Bonferroni corrected pairwise comparisons. All data are presented as mean \pm SD and a p -value <0.05 was considered statistically significant for all comparisons.

Results and Discussion

As expected, exposure to normobaric hypoxia resulted in a reduction in SpO₂ for all participants. Specifically, mean SpO₂ decreased from $97.0 \pm 1.3\%$ at 0.20 F_IO₂ to $95.8 \pm 1.6\%$ at 0.172 F_IO₂, $88.6 \pm 2.7\%$ at 0.145 F_IO₂ ($p < 0.001$ vs. 0.20 F_IO₂) and $81.1 \pm 3.5\%$ at 0.128 F_IO₂ ($p < 0.001$ vs. 0.20 F_IO₂), before returning to normal baseline levels ($97.7\% \pm 0.7$) (Figure 2). Visual inspection of the thermographic images revealed no artefacts or abnormalities. Visual comparison of the images did however reveal an apparent relationship between thermal emissivity and the level of hypoxia (Figure 3). Quantitative analysis of the thermographic data revealed an incremental decrease in surface body temperature at each of the four anatomical sites with increasing levels of hypoxia (Figure 4). Specifically, compared to measures of core body temperature, which remained stable across all levels of hypoxia ($p > 0.05$), surface body temperature decreased across all four anatomical regions with increasing levels of hypoxia ($p < 0.05$ at 0.128 vs. 0.20 (pre) F_IO₂, see Table 1). The most marked reductions in temperature were noted at the nail beds, with readings taken at the MCP joints showing only minor temperature changes; although this difference in change was not significant ($p > 0.05$). An increase in peripheral surface body temperature was demonstrated upon returning to baseline levels of F_IO₂ (0.20), however these changes were not statistically significant from 0.128 F_IO₂ and remained significantly lower than baseline values ($p < 0.05$, see Table 1). One explanation for this relates to the shorter time participants were exposed to the post-exposure 0.20 F_IO₂ condition. As such, a greater length of time may be required for thermal equilibration to occur following exposure to hypoxia. Nevertheless, these findings clearly demonstrate a link between hypoxia and the surface body temperature of the hands. Furthermore, here we have shown that these hypoxia-mediated variations in temperature can be detected using portable IRT. Consistent with the findings from earlier studies [Durand et al. 1969, Wood et al. 1970, Weil et al. 1971, Fahim, M. 1992], it is likely that these temperature reductions are the consequence of a decrease in perfusion to the cutaneous microvasculature in response to the activation of the sympathetic nervous system. Taken together, it is possible that these hypoxia-mediated reductions in

peripheral temperature may further compound the risk of developing frostbite and other cold-related injuries during exposure to low environmental temperatures at high altitude, but further investigation is required to conclusively elucidate this link.

At one time, cases of frostbite were almost exclusively seen amongst military personnel [Murphy et al. 2000], however in recent years the incidence of the condition amongst civilian populations of skiers and mountaineers has increased substantially [Hallam et al. 2010]. This can be attributed to the increased popularity of altitude-based sports and pursuits, but is also in part due to the improved accessibility and affordability of travel to extreme environments. To enhance the safety of these high-altitude tourists, several telemedicine services have been established [Pian et al. 2013], which provide a means of rapid and effective communication with a clinical specialist to aid the diagnosis and management of cold-related injuries. The application of new technologies in conjunction with these telemedicine services has the potential to further improve healthcare provision in remote environments. IRT is a simple non-contact, non-invasive imaging technique that provides an accurate quantitative measurement of surface body temperature. IRT has shown promise in several studies as a potential screening tool for the diagnosis of health conditions affecting the hands and digits [Chojnowski, M., 2017], including Raynaud's phenomenon [Ismail et al. 2014] and systemic sclerosis [Murray et al. 2009]. Although the results of this study have highlighted the potential of IRT as means of quantifying changes in surface temperature of the hands under hypoxic conditions of high altitude, there are several limitations to IRT that have hampered its clinical application to date; including the lack of standardised protocols, the calibration of the equipment, and the accuracy of the temperature readings that only provide an indirect measurement of tissue perfusion [Chojnowski, M., 2017]. However, despite these limitations, the potential applications of IRT as a diagnostic adjunct to existing telemedicine services should not be overlooked, and further assessment of its clinical applicability to the diagnosis and classification of frostbite and cold-related injuries should be explored further.

Conclusions

In conclusion, we have shown that exposure to normobaric hypoxia leads to a reduction in surface temperature of the hands, and that these temperature changes are detectable using portable infra-red imaging technology. Our findings provide support to the clinical application of IRT, although further confirmation of its diagnostic validity is required. The FLIR One thermal imaging camera is a compact, portable and inexpensive device that has the potential to aid the diagnosis and management of cold-related injuries occurring in remote and isolated environments.

Disclosure Statement

The authors declare no conflict of interests.

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Author Contributions

Study concept and design (DJ & CHEI); acquisition of the data (DJ, SFC, GEM, KIM, AGC, SDC & AMA); analysis of the data (DJ, SFC & SJEL); drafting of the manuscript (SFC); critical revision of the manuscript (SJEL, CHEI); and approval of final manuscript (DJ, SFC, GEM, KIM, AGC, SDC, AMA, SJEL, CHEI).

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